Micromachined convective accelerometers in standard integrated circuits technology

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This letter describes an implementation of micromachined accelerometers in standard complimentary metal–oxide–semiconductor technology. The devices operate based on heat convection and consist of microheaters and thermocouple or thermistor temperature sensors separated by a gap which measure temperature difference between two sides of the microheater caused by the effect of acceleration on free gas convection. The devices show a small linearity error of $<0.5\%$ under tilt conditions ($\pm 90°$), and $<2\%$ under acceleration to $7g(g \equiv 9.81\,\mathrm{m/s^2})$. Sensitivity of the devices is a nearly linear function of heater power. For operating power of ~ 100 mW, a sensitivity of 115 μV/g was measured for thermopile configuration and 25 μV/g for thermistor configurations. Both types of devices are operable up to frequencies of several hundred Hz. © *2000 American Institute of Physics.* [S0003-6951(00)04002-X]

Miniaturization and integration of accelerometers in standard integrated circuits (IC) processes has been the topic of extensive research.[1–3] In most cases, accelerometer structures involve solid proof mass, which is allowed to move under accelerating conditions. This has many disadvantages, the main one being difficult processing of such components in IC technologies inherently unsuited for such design. More recently, micromachining techniques have brought about many unique miniaturized accelerometer structures, although the fabrication includes many masks and etching steps. It would be very useful to integrate such devices in a standard complimentary metal–oxide–semiconductor (CMOS) technology, where on-chip drive and sense circuitry is available, and start-up costs are lower.

Recently, a new concept and device structure for acceleration and tilt sensing were developed by Dao *et al.*,[4] requiring no solid proof mass. The concept of operation of these devices is the effect of acceleration on the natural heat convection from heated resistive wires in a gas surrounding the device. In such a device, the sensor is hermetically packaged to prevent any influence of external airflow or pressure changes on the gas that surrounds the sensor. An implementation of this device structure by custom fabrication on a silicon substrate was reported recently by Leung *et al.*[5]

This letter reports on devices implemented in a standard CMOS utilizing micromachined thermopile or thermistor sensors for temperature sensing. Our process results in the provision of monolithic integration of drive, detection, and output circuitry with the sensor on a single chip. The capability of fabricating these structures in CMOS technology could have a significant economic advantage as a low-cost accelerometer with integrated electronics. In addition to miniaturization, integration, and lower cost, an advantage is a significantly improved frequency response (up to hundreds of Hz versus several to tens of Hz) when compared to other convective accelerometers.[4,5] Also, our devices show significantly lowered power requirements, especially the novel thermopile configuration.

The basic part of the devices is a suspended polysilicon microheater.[6] The thermal difference between the heated element and the surrounding gas generates the buoyant force that causes the convective flow of the gas. When acceleration is applied, the change in the convective flow causes a temperature difference between sides of the heated element. This temperature difference is proportional to the applied acceleration, and temperature sensors placed on either side of the heat source measure a differential output corresponding to the applied acceleration. Temperature sensing can be based on thermocouple or thermistor effect. We have implemented both types of devices, due to the inherent capability of CMOS layers for both types of measurements. Microphotographs of the fabricated thermopile device, and the thermistor device are shown in Figs. 1 and 2, respectively.

In the thermopile device of Fig. 1, the meandering polysilicon heater encapsulated in glass passivation is seen in the center, suspended in air to obtain high thermal efficiency. The figure also shows two sets of closely spaced thermocouple junctions located on either side of the heater. Each of

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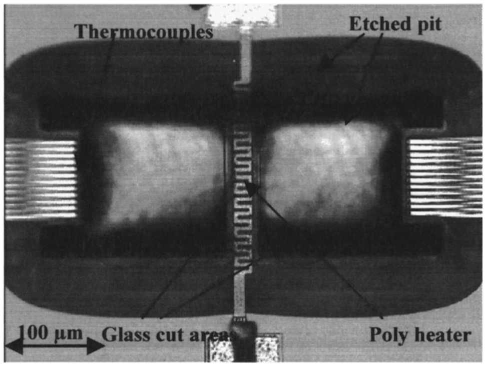

FIG. 1. Microphotograph of the fabricated thermopile-based CMOS-compatible convective accelerometer.

these hot junctions is in series with a cold junction located above the base silicon material. There are altogether 12 thermocouples connected in series on each side of the sensor to increase the output voltage signal. The final raw output voltage is taken as the difference of the outputs of the thermocouple sets on either side.

For the thermistor devices, the principle is the same, but a different configuration is utilized (Fig. 2), as used in Ref. 4. Two parallel polysilicon resistors are fully suspended with an adequate air-gap separating them. They are placed in a Wheatstone bridge circuit with reference to two parallel ''cold'' resistors, which are not suspended, as shown in Fig. 2. As a result of micromachining, the two parallel heaters are both at the same high temperature until convective air flow is made asymmetric by the influence of acceleration along the sensitive axis.

Test chips were fabricated in a 2 μm CMOS process through the MOSIS service, and were subsequently etched in our laboratory at NIST.[3] In Fig. 1, the glass-cut areas are on both sides of the heater. In Fig. 2, there is a large glass-cut area between the two parallel resistors, and thin glass regions on either side for better thermal isolation. The devices were silicon micromachined[3] using a gaseous isotropic etchant, xenon-difluoride. After approximately 6 min of etching the structure is entirely suspended, up to the cold thermocouple junctions which must remain on the silicon substrate. The resulting devices are adequately thermally isolated from the substrate to achieve temperatures as high as 1000 K for very small input powers (<100 mW for device in Fig. 1). Better uniformity and etch-stop control could be obtained by employing the hybrid technique that we utilize in some other applications.[3]

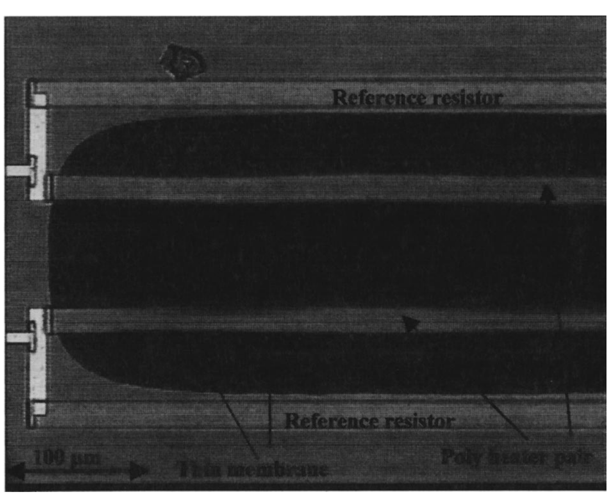

FIG. 2. Microphotograph of the fabricated thermistor-based accelerometer.

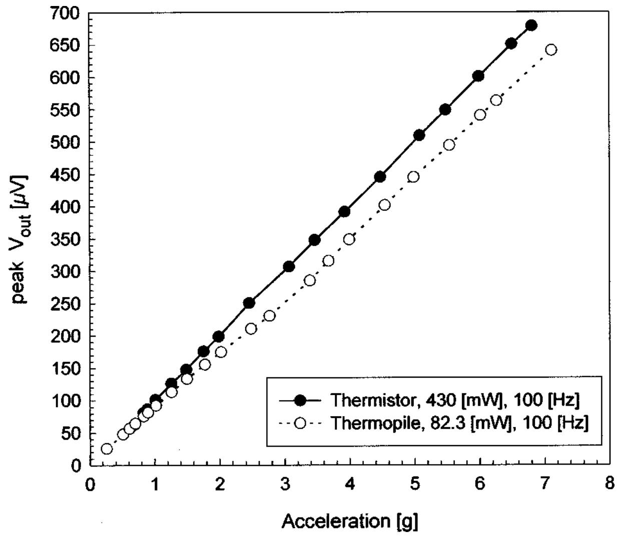

FIG. 3. Measured performance of the accelerometers from 0 to 7 g acceleration at 100 Hz.

Measurements were performed under various applied conditions. First, the sensor was mounted on an optical goniometer and tilted from $\Theta = -90$ to 90 degrees of angle, where Θ is the angle between the chip's surface normal and the gravity vector. For this test, constant external power was applied to the heater instead of constant voltage or current, to achieve a high bias stability of the suspended polysilicon resistor.[6]

The devices were subsequently measured on a vibration exciter (shaker), with acceleration range from 0 to 7 g and vibration frequencies from 30 Hz to 3.0 kHz. Figures 3 and 4 show the measured outputs in terms of linearity and frequency response. Another important measurement is the sensitivity of the device while varying the input power to the microheater, i.e., varying the driving temperature. These measurements were also under conditions of applied accel-

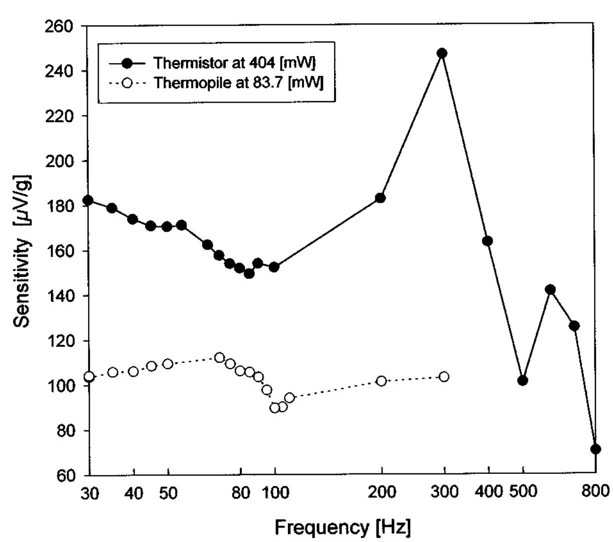

FIG. 4. Measured sensors' frequency responses (frequency sensitivity).

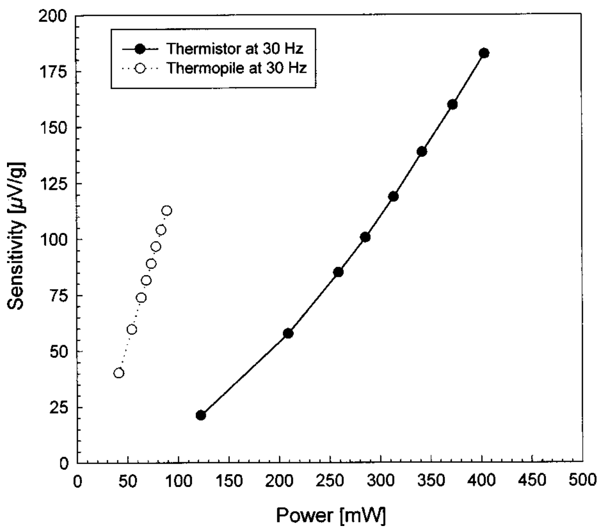

FIG. 5. Measured sensors' power sensitivity at 30 Hz.

eration on the shaker, and the results are given in Fig. 5 for both devices.

The measured voltage in tilt testing[7] showed a very good fit to the sine function as expected, since the equivalent acceleration projected on the sensitive axis of the device is proportional to $g\ \sin(\Theta)$. Plotted linearly as acceleration versus output voltage, linearity error of $<0.5\%$ was computed for both types of devices.[7] A sensitivity of 136 μV/g at 81 mW was measured for the thermopile type, and 146 μV/g at 430 mW for thermistor. Measurements of output voltage at applied acceleration shown in Fig. 3 also demonstrate very good linearity of both devices in the range from 0 to 7 g. The measured output voltage of Fig. 3 has a larger linearity error than in the tilt measurements, although still $<2.6\%$ over the 7 g applied acceleration range. In comparison of the two devices, similar sensitivities are obtained at operation voltage of roughly 24 V, but in the case of the thermopile configuration, significantly less power dissipation is needed.

The thermopile devices also show very promising results for the frequency response in Fig. 4, which is fairly flat up to about 100 Hz, where the device's sensitivity decreases substantially. At the same time, the thermistor device appears to have a higher frequency response: it responds up to several hundred Hz, although with significant fluctuations. The higher frequency response is believed to be due to the significantly smaller spacing between sensing devices, while the source of fluctuations is currently unknown. Overall, the frequency characteristics are satisfactory, and demonstrate that this concept for inertial sensors gains much from the IC microtechnology.

Finally, the measurements in Fig. 5 demonstrate the dependence of sensitivity to the change in applied power to the heater. This result was expected since the driving mechanism for the convection is the temperature difference between the microheater and the overall package. With linear increase in temperature, the sensitivity showed a proportional increase with a slope of 1.5 and 0.67 μV/g mW for the thermopile and thermistor device, respectively. This is also an important result because it shows that for higher g applications, and with more sensitive output circuitry, power consumption could be significantly decreased for these devices.

The above results were measured in the presence of noise, which is dominated by the thermal noise of thermopile/thermistor resistance. The thermal rms noise voltage V_n is defined as $V_n=(4kTR_{\mathrm{tp}}B)^{1/2}$, where k is the Boltzmann constant, T is the absolute resistor temperature ($\sim$room in our case), B is the bandwidth of interest, and R_{tp} is the thermopile resistance. For the thermopile device, the resistance was 64 kΩ, giving noise voltage of 32.6 nV/Hz$^{1/2}$, while for thermistor device, and resistance of 4 kΩ, noise voltage was 8.14 nV/Hz$^{1/2}$.

The measurements presented here were performed on the devices packaged in ambient air. Since the sensors are convection-based, work is under way to characterize them in various gases, and under higher gas pressures, to achieve higher sensitivity.[5]

We have reported on the configurations of convective accelerometers for numerous applications. The sensors were fabricated in low-cost CMOS technology with one additional maskless post-processing step. The devices showed good sensitivity and linearity characteristics, as well as a large range of operating frequency response. The CMOS implementation gives the advantages of low cost and easy integration with CMOS circuits. Much further work is needed to optimize the device and characterize performance using different gases, pressures, geometries, and temperatures.

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